CONF-800918--5

LA-UR-80-2589

TITLE: MAGNETIC ENERGY STORAGE

AUTHOR(S): John D. Rogers

SUBMITTED TO: Applied Superconductivity Conference, Santa Fe, NM, September 29-October 3, 1980

MASTER

los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

Form No. 836 R2
St. No. 2629
1/78

DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

MAGNETIC ENERGY STORAGE*

John D. Rogers
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

Abstract

Magnetic energy storage has become the foundation for near time and longer range electric utility applications and for current induction in the plasma of fusion devices. The fusion program embraces low loss superconductor strand development with integration into cables capable of carrying 50 kA in pulsed mode at high fields. This evolvement has been paralleled with pulsed energy storage coil development and testing from tens of kJ at low fields to a 20 MJ prototype tokamak induction coil at 7.5 T. Energy transfer times have ranged from 0.7 ms to several seconds. Electric utility magnetic storage for prospective application is for diurnal load leveling with massive systems to store 10 GWh at 1.8 K in a dewar structure suported on bedrock underground. An immediate utility application is a 30 MJ system to be used to damp power oscillations on the Bonneville Power Administration electric transmission lines. An off-shoot of this last work is a new program for electric utility VAR control with the potential for use to suppress subsynchronous resonance. Pulsed magnetic energy storage is not a widely developed technology. Current work is done almost exclusively in Japan and the United States. This paper does not cover past work or completed studies but presents work in progress, work planned, and recently completed unusual work.

Summary

Superconducting magnetic energy storage has its roots in providing a pulsed source of energy or an energy supply to be provided over a long time period. The former embraces high intensity flash lamp energy systems, accelerator drives, and magnetic confinement fusion systems, principally for plasma current induction and ohmic heating. The latter is for diurnal load leveling for an electric utility system. More recently, superconducting magnetic energy storage to stabilize negatively damped power oscillations on an electric utility transmission line and for VAR control on an electric utility system requires a biased energy storage with a low frequency energy flow with only a fraction of the stored energy going in and out of the storage coil.

Aggressive programs, both in the United States and Japan, are the principal magnetic energy storage technology development efforts.

The International Tokamak Reactor (INTOR) and Engineering Test Facility (ETF) design studies have indicated the need for additional pulsed energy storage work to advance the technology base to a level commensurate with the tokamak toroidal field coil development. Work underway at the Los Alamos Scientific Laboratory (LASL) is to demonstrate engineering feasibility for the ETF central solenoidal ohmic heating coil with prototype 20 and 100 MJ coils to operate in a ± 7.5 T bipolar mode with 50 kA maximum current. The Argonne National Laboratory[1] is relying on their 1.5 MJ pulsed superconducting coil experience to build a 6.4 T background coil to develop 50 to 100 kA superconducting cable for ETF.

*Paper prepared under the auspices of the U.S. Department of Energy.

Additionally, LASL is engineering a 30 MJ Superconducting Magnetic Energy Storage (SMES) system to damp power oscillations on the Bonneville Power Administration (BPA) HVAC transmission lines which run from the Pacific Northwest to southern California.

Static VAR compensation systems are used by the electric utility industry. The possibility exists that VAR compensation can be provided with superconducting coils with relatively small energy storage of a few hundred kilo joules. A program to determine the applicability of such a system has been initiated at LASL.

The Japanese have successfully built and operated a number of small pulsed energy storage coils. Their goals for future work include a 0.5 MJ energy storage and transfer system in 1980 at Osaka University, a 100 MJ ohmic heating coil prototype five year program at JAERI, and a 1 MWh toroidal diurnal load leveling (SMES) demonstration to be operational for the 1985 International Science Exposition to be held in Tsukuba Science and Education City, Japan.[2] Shintomi et al.[3] have reported on a 300 kJ superconducting shielded coil for pulsed energy storage which utilizes the unique scheme of Moses and Ballou.[4]

Both the University of Wisconsin (UW) and LASL have made extensive preliminary conceptual engineering reference designs of diurnal load leveling SMES systems.[5,6] UW has concentrated on development of conductor, structures, and cryogenic components.[7] Recent LASL work now in progress is to design a wire rope conductor. The study of Winer[8], contrary to an earlier analysis,[9] concludes that SMES is economically competitive compared with other large energy storage systems when the rated energy delivered exceeds about 1750 kWh/yr per kW.

ETF Ohmic Heating Coil System

The ETF ohmic heating coil is sized to induce 4.9 MA plasma current in 6 s. The central solenoid coil set is shown in section in Fig. 1, and the main features are tabulated in Table I. The coil set is to be of pancake design and have a maximum field of 7 T at a current of 50 kA superconducting cable rating. The details of the design follow closely the LASL 20 MJ prototype coil.

Ohmic Heating Coil and Cable Development

A prototype 20 MJ superconducting ohmic heating coil capable of being scaled to the ETF size is to be made and tested. The coil was designed by Westinghouse Electric Corp. on contract to LASL and manufacture has been started. An outline drawing of the coil is shown in Fig. 2, and Table II gives some of the characteristics. The coil is to be made of four double pancake windings on epoxy fiberglass structure with a maximum field of 7.5 T at a current of 50 kA. The coil is to be tested with a full bipolar energy transfer with complete current and field reversal in 1.3 s.

Testing of the coil with a full reversal in the short time of 1.3 s instead of the 6 s ETF current induction period was decided in consultation with the ETF Design Center. In the event an appropriate preheat system is not available, the development of a coil to satisfy the shorter pulse time provides greater ETF

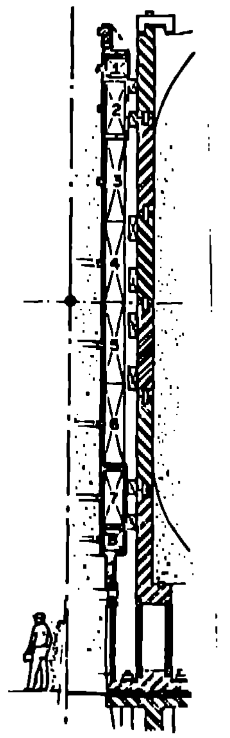

Fig. 1. ETF central solenoid coil set. (Courtesy ETF Design Center ORNL.)

TABLE I
ETF OHMIC HEATING COIL

Field, maximum, T	7
Current, kA	50
Winding	pancake
Outside radius, m	1.6
Inside radius, m	1.2
Current density overall, A/cm^2	1500
Energy stored, GJ	1.8

design latitude. Testing of the coil is to be done with a resonant circuit, Fig. 3, which uses electromechanical capacitors. Sixteen General Electric type 752 traction motors have been purchased for this purpose. Flywheels are to be added to the motors to augment the armature inertia to store the energy during transfer. Operation of the test circuit is to charge the coil with S3, a bypass switch, closed. S1 and S2 are closed temporarily while S3 is opened. S1 and S2 are opened and the coil energy transfers into traction motors and back. The power supply is reversed and is crowbarred by closing S1 and S2 and then S3 to hold the charged coil at the end of the transfer period. R1, R2, C1, and C2 are protective resistors and voltage surge suppressors. The energy transfer period can be controlled by adjusting the field winding current. The same system can be used to test 100 MJ coils by using larger flywheels.

A prototype length of 50 kA cable for the 20 MJ coil has been made by Intermagnetics General Corp. and is shown in Fig. 4. Stability measurements on one of the 36 subcables, extrapolated to the full cable size, gives a recovery current in excess of 64 kA as predicted. Tests on the full 50 kA cable will be run in the Lawrence Livermore Laboratory MFTF high field conductor test facility as a background coil to confirm the stability limit.

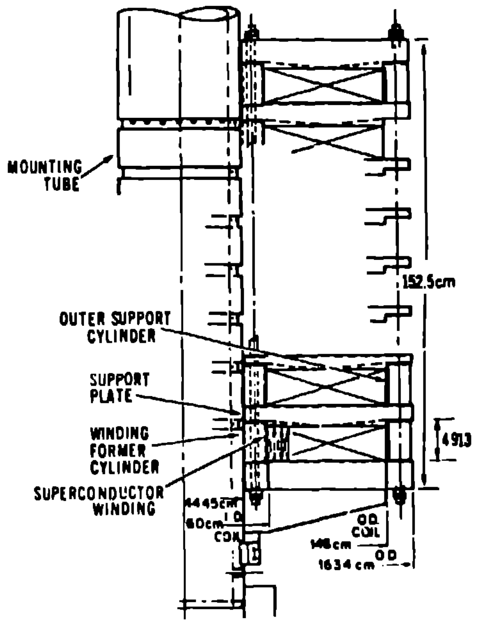

Fig. 2. 20 MJ tokamak ohmic heating prototype coil.

TABLE II
20 MJ PROTOTYPE COIL

Field, maximum, T	7.5
Cooling	pool boil at 4.5 K
Winding	double pancake
Current, kA	50
Turns per pancake	25
Overall current density, A/cm^2	1716

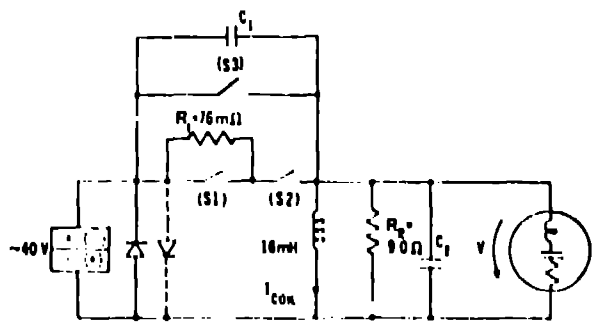

Fig. 3. 20 MJ coil test circuit.

The Argonne National Laboratory is building on the successful 1.5 MJ pulsed superconducting coil of Kim et al.,[10] which was operated into the current sharing region up to 11.2 kA and for many cycles with low losses. Efforts are underway to extend pulsed superconducting magnet development toward the high current, 50 to 100 kA, high pulse rate, up to 10 T/s, superconducting ohmic heating coils needed for a tokamak ETF.

Fig. 4. 50 kA prototype cable for 20 MJ coil.

A Pulsed Cable Test Facility (PCTF) is under construction which will permit the testing of superconducting cables needed for these coils. The key component of the facility is a large pulsed superconducting magnet which will generate a field of 6.4 T in an adjustable gap where high current pulsed cable samples as wide as about 10 cm can be mounted for testing in a pancake winding. The coils of the facility will store 3.5 MJ and can be pulsed at 6 T/s using an existing power supply. Studies are underway to utilize the PCTF magnet itself as a companion to the existing 1.5 MJ coil for energy storage and transfer at ~10 kA current. A schematic drawing of the dewar coil set is shown in Fig. 5 and some characteristics are given in Table III.

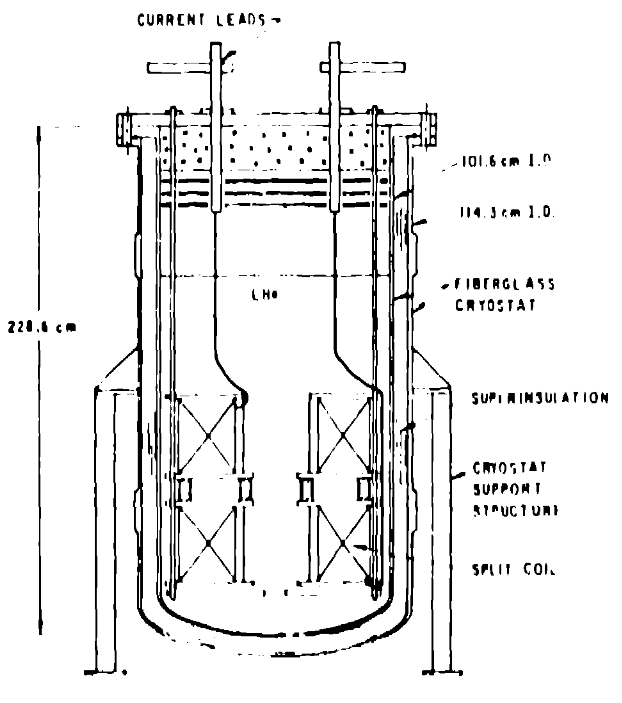

Fig. 5 PCTF dewar and split pair solenoid. (Courtesy of Argonne National Laboratory.)

Electric Transmission Line Stabilizer

The Pacific Northwest and southern California are part of the Western U. S. Power System and are connected by two 500 kV, ac power transmission lines with a thermal rating of 3500 MW. The lines are operated by the Bonneville Power Administration (BPA). System stability system is affected by the relative weaknesses in the 900 mile long lines connecting the areas. In 1974, predicted negatively damped oscillations of about 300 MW amplitude at 0.35 Hz were observed[11] on the transmission lines. One means of preventing the oscillations is to apply a low amplitude, up to ± 5 MW, out of phase signal to the lines. This is to be done with a 30 MJ, 5 kA, 2.8 T energy storage coil being made by General Atomic Co. on contract to LASL. The coil is interfaced to the transmission line through a converter and power transformers shown to the left of the artist's concept of Fig. 6. The cryogenic system is to the right of the figure. Table IV gives some of the coil characteristics. The SMES unit is to be installed at the Fite Substation, Tacoma, WA, and operated completely remotely over a microwave link from Portland, OR.

TABLE III
PCTF ENERGY STORAGE COIL

Field, maximum, T	6.4
Current, kA	11
Winding	multi layer
Outside diameter, m	0.88
Inside diameter, m	0.45
Height, m	0.64 + gap
Current density, A/cm^2	3685

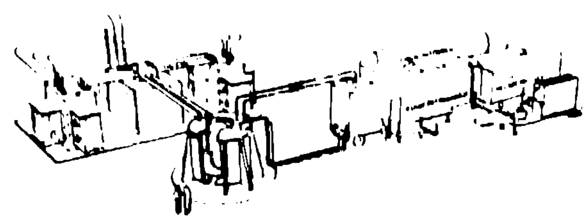

Fig. 6. Artist's concept of BPA 30 MJ SMES coil.

TABLE IV
BPA 30 MJ SMES COIL

Field, maximum, T	2.8
Winding	double pancake
Number pancakes	40
Number turns	920
Current, kA	4.9
Mean radius, m	1.53
Radial thickness, m	0.33
Height, m	1.21

Reactive Power Control

Static reactive power (VAR) control systems with thyristor controlled, room temperature reactors are used in electrical systems for voltage control and system stabilization. The possibility of using a small superconducting energy storage coil of a few hundred kilo joules with a variable controlled Graetz bridge has possibilities for a new direction for VAR control.[12] The system is being analyzed by LASL and Westinghouse to determine the economic potential before a full scale program is undertaken. Experiments by Boenig[13] show the circuit behaves as predicted. A superconducting coil for a 40 MVAR system would require an iron core with air gaps or a shielded coil[4] to have low losses. A preliminary parameter study was undertaken and one set of coil characteristics is given in Table V.

Japanese Energy Storage

The Japanese effort to develop energy storage for fusion, electric utility, and accelerator applications has assumed a growing role in their superconductivity program. Four of these new efforts are presented.

0.5 MJ Pulsed Superconducting Coil System

A pulsed energy storage system composed of a 0.5 MJ superconducting energy storage coil and a 12 pulse thyristor Graetz bridge converter circuit is to be located at Osaka University.[14] The system will be used to develop superconducting material, control system, and cooling system technology. The Graetz bridge system is computer controlled with system variables sensed to provide inputs to feedback loops. The bridge output can operate in parallel or series to provide 1000 A at either 500 or 1000 V, respectively. Some of the storage coil features are given in Table VI.

JAERI Pulsed Coil Development

The pulsed energy storage coil work of the Japan Atomic Energy Research Institute (JAERI) is being evaluated and now includes a tentative plan for a 100 MJ, 50 kA, 8 T coil for testing in five years. A suggestion has been made to Japan to enter into a cooperative program for building and testing such a coil with LASL.

The tentative five year JAERI program[15] is to develop in sequence 10 kA and 50 kA, 7 T superconducting cables. The 10 kA cable is to be made into a small coil to be fast and slow pulse tested in a 5.5 T background coil. The results will be used together with the 50 kA cable development for information to build a 50 kA, 7 T, 10 MJ energy storage coil. If the 10 kA cable is used, the 10 MJ coil should be available for testing in the third year and the fourth year if the decision is to use the 50 kA cable. The fabrication of a 100 MJ coil, made of two sub coils, is planned for the third and fourth years with testing to be done during the fifth year of the program. Power supplies for the testing are conceived to be installed in stages, first to provide 30 kA and later in time, two power supplies combined to have a 70 kA output. The parameters for the 100 MJ coil are presented in Table VII.

1 MWh Diurnal Load Leveling Demonstration

A 1 MWh diurnal load leveling electric utility toroidal demonstration unit will be built for the International Science Exposition to be held in Tsukuba Science and Education City, Japan, in 1985.[2] The energy stored will be 3.6 $(10)^9$ joules. The coil is to be made of fully stabilized NbTi in copper matrix 5 kA conductor. The project will rival the LCP at Oak Ridge in scale and is estimated to cost between $9 and $18 million. A sketch of the toroidal storage coil assembly is shown in Fig. 7 and characteristics are given in Table VIII.

TABLE VII
100 MJ COIL PARAMETERS

Maximum field, T	8
Pulsed field, T/s	10
Winding i.d., mm	1200
Winding o.d., mm	2000
Sub winding height, mm	600
Winding gap, mm	150
Total height, mm	1350
Operating current, kA	50
Number or turns	240
Stored energy, MJ	105
Current density, A/mm²	25

TABLE V
COIL CHARACTERISTICS FOR VAR CONTROL SYSTEM

Current, kA	2.14
Gap, cm	18
Turns	80
Inductance, mH	54
Field in iron, max., T	1.14
Field on coil, T	0.53

TABLE VI
0.5 MJ COIL CHARACTERISTICS

Field, T	5
Winding	double pancake
Turns	1020
Current, kA	1.9
Outside diameter, mm	500
Inside diameter, mm	310
Axial length, mm	280

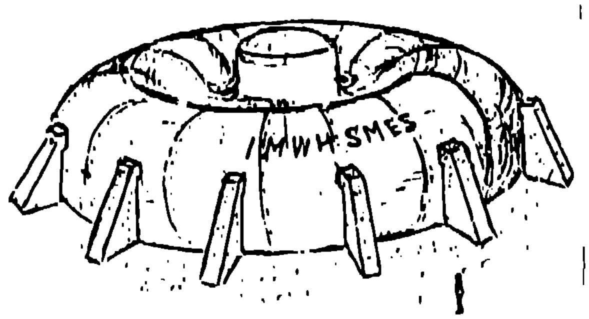

Fig. 7. Twelve coil toroidal 1 MWh diurnal load leveling demonstration unit. (Courtesy M. Masuda.)

TABLE VIII
1 MWh DIURNAL LOAD LEVELING UNIT

Energy stored, J	$3.6(10)^9$
Major radius, m	6.9
Minor radius, m	3.5
Inductance, H	288
Current, kA	5
Number of coils	12

Shielded Magnet for Pulsed Energy Storage

Moses and Ballou[4] describe a shield coil assembly which uses a solenoidal winding nested in a set of surrounding solenoidal coils in a poloidal array. In practice, all the individual coils have a low height to radial thickness aspect ratio. The central coil is generally conceived as a dc cryogenically stable superconducting dipole with the surrounding shield coils being ambient temperature copper conductors. The shield coils are arranged to keep the leakage field on the superconducting coil to a very low value. The superconducting dipole is not exposed to alternating currents or magnetic fields and, hence, is stable. A 300 kJ model shielded coil has been reported by Shintomi, et al.[3] for testing with possible large scale applications for accelerators drives, fusion device power supplies, and electric utility applications. The assembly is shown in Fig. 8 and Table IX has the published parameters.

Diurnal Load-Leveling Storage System

Energy storage on a large scale in superconducting coils up to 10 GWh holds promise for efficient energy transfer as high as 90 to 95% because there is no transformation of the form of energy. Electric utilities would use such systems for diurnal load leveling and Winer and Nicol[8] have shown a clear advantage for Superconducting Magnetic Energy Storage (SMES) when the SMES systems store about 5 GWh or more or better yet deliver in excess of about 1750 kWh/yr per kW. Cost studies of reference designs[5,6] vary as much as factors of 2 to 3. Regardless, in large sizes, SMES systems appear competitive with other types of

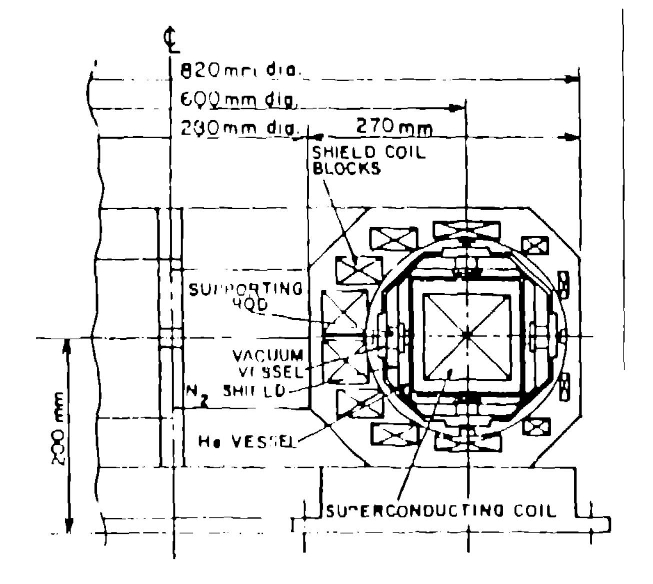

Fig. 8. 200 kJ shielded pulsed energy storage coil.

TABLE IX
200 kJ SHIELDED COIL PARAMETERS

Superconductive Coil	
Energy stored, kJ	200
Inductance, H	0.23
Current, A	1350
Current density, A/cm^2	1.1×10^4
Turns	528
Field, T	4.0
Major radius, cm	30
Cross section, cm	8.4 x 7.6
Cooling mode at 4.2 K	pool boiling
Superconductor	
Material	Nb-Ti/Cu
Critical current at 5 T, 4.2 K	1770
Cu/SC ratio	3.9
Filament diameter, μm	32
Filaments	1250
Twisted pitch, mm	25
Shield Coil	
Inductance (self), H	0.082
(mutual), H	0.089
Current, A	200
Current density, A/cm^2	910
Energy available, kJ	50
Turns	528
Cross section, mm	4 x 5.5
Resistivity at 300 K, Ω	0.77
Material	OFHC copper

energy storage. The system design studies have shown that beneath the ground construction with bedrock support of the magnetic pressure on the conductor and operation in 1.8 K superfluid helium are economic.

Previous work,[7] besides the preliminary conceptual engineering designs, involves room temperature testing of warm wall rock to conductor plastic-fiberglass support structures and development of prototype conductor. More recent studies by the University of Wisconsin indicate that low fields combined with very large diameter SMES storage coils allow the coil to be much closer to the surface for structural support at a potential cost saving.[16] The concept, new for the main storage coil, is developed in a different way for a SMES guard coil buried right at the surface and supported by a low cost concrete foundation.[5,6] The concept of a flexible wire rope made of a multi strand structural stainless steel core surrounded by copper and copper matrix NbTi superconducting subbundles for ease of fabrication into a 50 kA cable has been considered by LASL and appears feasible for diurnal load leveling coils.

Conclusion

Superconducting magnetic energy storage is a rapidly developing technology. A number of potential applications are being pursued on a scaled basis and for demonstration to lead to larger prototypes and full scale applications. Magnetic energy storage systems have applications as power supplies for accelerators, coils to induce current into and provide ohmic heating of plasmas in fusion devices, stabilizing systems for electric utility transmission networks, and reactors for reactive power compensation for electric utility systems.

Acknowledgments

The author expresses his appreciation to the many persons referenced in this paper for advanced information on aspects of their projects and particularly to K. Yasukochi, S. Shimamoto, Y. Murakami, and M. Masuda, who communicated much of the advance information on the Japanese programs.

References

1. S. H. Kim, R. P. Smith, R. Kustom, W. F. Praeg, C. I. Krieger, "Development of a Pulsed Cable, Test Facility for Superconducting Ohmic Heating Coils, paper FA-29 this conference.
2. M. Masuda personal communication.
3. T. Shintomi, M. Masuda, Y. M. Eyssa, R. W. Boom, "Design and Construction of a 200 kJ Shielded Magnet for Pulsed Energy Storage," 8th Int. Cryog. Eng. Conf., June 3-6, 1980, Genoa, Italy.
4. R. W. Moses, J. K. Ballou, "Inductive Shielding for Pulsed Energy Storage Magnets," IEEE Trans. Mag. MAG-11, 493-496(1975).
5. "Wisconsin Superconductive Magnetic Energy Storage Project" University of Wisconsin Vol. I (July 1974), Vol. II (Jan. 1976), and Annual Report (May 1977).
6. "1-GWh Diurnal Load-Leveling Superconducting Magnetic Energy Storage System Reference Design," Los Alamos Scientific Laboratory reports LA-7885-MS Vol. I through VIII (1979).
7. S. W. Van Sciver, R. W. Boom, University of Wisconsin, "Component Development of Large Magnetic Storage Units," Proc. 1979 Mechanical and Magnetic Energy Storage Contractors Review Meeting, Wash. D. C. , Aug. 1979, Conf-790854.
8. B. M. Winer, J. Nicol, "An Evaluation of Superconducting Magnetic Energy Storage," Arthur D. Little, Inc. report C-82820 (Nov. 1979) and paper EA-2 this conference.
9. Public Service Electric and Gas Co., "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities," EPRI EM-264 and ERDA E(11-1)-2501, (July 1976).
10. S-H. Kim, S-T. Wang, M. Lieberg, Adv. Cryog. Eng. 25, 100(110710); S-H. Kim, S-T. Wang, W. F. Praeg, C. I. Krieger, M. Lieberg, IEEE Trans. Mag. MAG-15,840(1979).
11. R. L. Cresap, W. A. Mittlestadt, IEEE-PAS 95, 536(1976).
12. H. J. Boenig, W. V. Hassenzahl, "Application of Superconducting Coils to VAR Control in Electric Power Systems: A Proposal," Los Alamos Scientific Laboratory report LA-8055-P (1979). The conclusion in this report that no air gap is required in the iron core is in error.
13. H. J. Boenig, W. V. Hassenzahl, personal communication and paper FA-33 this conference.
14. T. Okada, Y. Murakami, J. Yamamoto, Y. Inuishi, A. Mitsuishi, "0.5 MJ Superconducting Pulsed Magnet for Energy Storage Experiments," paper FA-30 this conference.
15. H. Tsuji, K. Okuno, Y Takahashi, T. Ando, S. Shimamoto, K. Yasukochi, "A Conception for Superconducting Poloidal Coil Development Program," preprint.
16. R. W. Boom, paper EA-1 this conference.